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RESEARCH PAPER

Forest biomass density, utilization and production dynamics in a western Himalayan watershed

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Abstract: There is enough evidence to show that the forest biomass has decreased significantly in the Indian Himalayan state of Himachal Pradesh. The government has responded through restrictive measures to check this decline. Using tree biomass as proxy for degradation, we assessed the current state of biomass within dominant land use types and examined its implications for sustainability. The highest above-ground mean tree biomass density of 1158 $t \cdot ha^{-1}$ was recorded for the reserved forest followed by 728, 13, 11, 8, 5 and 3 $t \cdot ha^{-1}$ in the protected forest, fallow land, cultivated-unirrigated land, grassland, orchard land and cultivated-irrigated land respectively. Of the total accessible biomass, only 0.31% was extracted annually by the local people for fuel, fodder and other uses. Though, the current level of extraction may be sustainable in the short run, insufficient regeneration is observed for long term sustainability. Forest biomass production was simulated for the next 30 years with a logistic growth model and the relative significance of input variables in influencing system behaviour was analysed through sensitivity analysis. The model results highlighted the declining forest resources in the long run. Positive response through appropriate government policies can, however, change the scenario for the better.

Keywords: Biomass density; Carrying capacity; Forest degradation; Fuel wood; Himachal Pradesh; Mean annual increment

Introduction

Himalayan forests have been under continual threat of deforestation and degradation for thousands of years posing a serious ecological crisis in these inherently fragile ecosystems (Ives and Messerli 1989). Forest Survey of India (FSI) regularly assesses the above-ground tree biomass of forests at a national scale by integrating remote sensing data with the field inventory data. Results from this analysis have shown that the forest biomass in the Indian Western Himalayan state of Himachal Pradesh has decreased significantly over a period of time (FSI 2003). According to this study, dense forest cover (crown density above 40%) declined by 10% and contributed to the open forest cover (crown density 10% to less than 40%), along with a complete conversion of many forest areas to developments, agricultural land or pastures between the years 2001 and 2003. Such a phenomenon is indicative of the ongoing degradation of forests in Himachal Pradesh. Taking reduction in biomass density as an indicator of forest degradation, this is an alarming situation for local people dependent on forest resources. This phenomenon also affects the people in the plains due to increased runoff during rainy season, leading to flash floods and reduced water supplies at other times. At the global scale, such degradation may reduce carbon sink potential.

The state level data documenting biomass decline are aggregated at a course resolution rendering it unfit for use in developing effective region specific policies for the sustainable use of forest resources. This emphasizes the importance of undertaking inventories of biomass and its usage at a micro watershed level. Ideally, biomass estimation should be done by following direct method, where total harvesting of trees or sample harvesting is done (Usotsev and Hoffman 1997). Though the direct method is more accurate and a good basis for indirect approaches, it is rarely employed due to economic and environmental constraints. Therefore, a feasible alternative is to adopt indirect methods, such as allometric relations with basal area, height or stem density (trees/ha) (Brown et al. 1991; Palm et al. 1986; Whitmore 1984). It explains why most of the studies in the region on its estimation have resorted to indirect approaches (Chaturvedi and Singh 1982; Rawat and Singh 1988). However, the efforts at estimation of biomass density by different land categories have rather been scarce. This study represents an attempt to fill such gaps in existing knowledge.

The overall objective of the study is to estimate the above-

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ground tree biomass density and its utilization and analyse its production dynamics in a micro watershed in the Indian Himalayan state of Himachal Pradesh. Structural and biological attributes of tree species and their relative significance on each land use category are also explained. Based on these field observations and the determinants of biomass growth, suitable policy recommendations have been made for the sustainable use of forest resources in similar micro watersheds in the region. These recommendations are more likely to serve as a valuable reference for sustainable management of forest resources in other parts of the world with similar ecological and socio-economic conditions.

Materials and methods

Study area

Chabri micro watershed is situated (latitude 30º57′–30º 58´30″N and longitude 77º10′–77º 12′E) in Solan district of Indian state of Himachal Pradesh (Fig. 1). This watershed falls in the wet-temperate forest zone of Himachal Pradesh (GOHP 2002). This zone constitutes about 31% of the state forest cover (GOHP 2007). The entire state constitutes a major natural watershed in north Indian region encompassing watersheds of four major tributaries of Indus, namely, Chenab, Ravi, Beas and Satluj, and that of Yamuna. The micro watershed under study is a catchment area of Chabri, a rivulet that drains into Ashwani, a tributary of Yamuna. It is a small mountainous oval shaped valley with steep slopes, typical of the landscape pattern in the mid hill zone of the state. Due to the differences of moisture availability, northern slopes of the watershed are densely forested, while southern slopes have mainly grasslands, mixed with patches of forest and scrub. Altitude of the watershed ranges from 1600 to 1950 m a.s.l. The average temperature varies from -4ºC to 28ºC during a year. The average annual rainfall during the period 1993–2003 was 596 mm and snowfall was 65 cm (GOHP 2005).

The watershed measuring about 8.96 km^2 has nine villages and 102 households with a human population of 703 and livestock population of 471 (266 indigenous cattle, 174 crossbred cattle and 31 buffaloes). According to official records, about 58% of the watershed area is under state-owned forests classified as reserved forests and demarcated protected forests. These two types of forests in the watershed fall in the category of Himalayan temperate forest as per the classification by Champion and Seth (1968), where coniferous trees and broad leave trees are in existence separately at some places or in mixture at others. Being located in the dense forest region, the inhabitants of the watershed have significant dependence on forest biomass for meeting their requirements of fuel wood, timber, fodder and grazing. Due to the diversity of flora and fauna in the region, a total area of 108 km^2 was declared as sanctuary in 1976, of which this micro watershed is a part (GOHP 2005). Extraction of all forest products by the local people have been prohibited since late nineties due to interim orders passed by the Indian Supreme Court in response to Public Interest Litigation (PIL). These orders prohibit all forest activities like the removal of any dead or decaying trees, grass, and driftwood from any area comprising of a National Park or a Sanctuary (Sekhsaria and Vagholikar 2004). Prior to these orders, people had full usage rights for the extraction of forest products. Following these orders the timber distribution rights of people in the forests were annulled. Although, logging activities are strictly prohibited, people freely extract fodder leaves and grass, fuel wood, small wood for different uses and graze animals in the forests. Logging rights in the forests were also recently banned throughout the state by an interim-order passed by the High Court of Himachal Pradesh in 2006 in response to a PIL (UNI 2006).

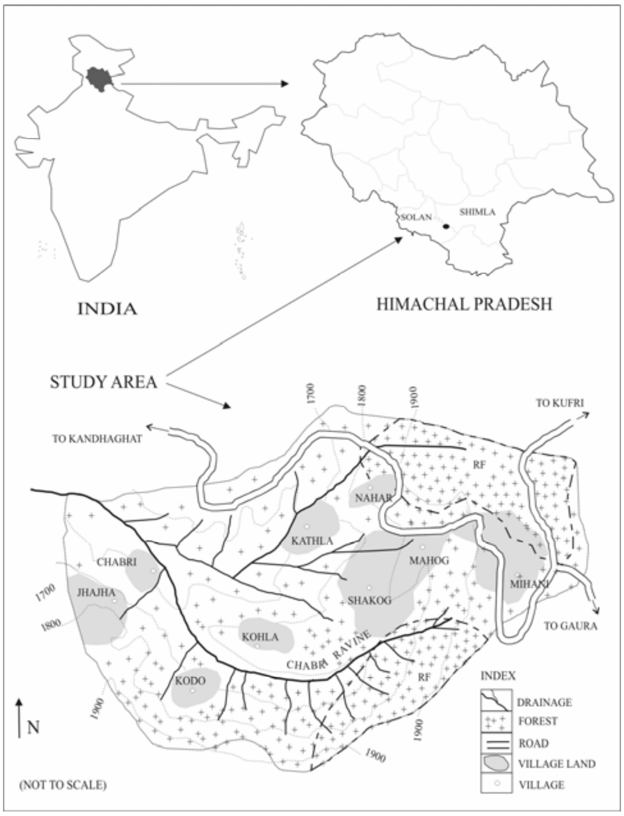

Fig. 1 Map of the study area

Forest inventory data

Data on tree biomass were collected by locating 70 square shape plots in the six dominant land use categories used in this study. Necessary details on number, shape, area, etc., of these plots in different land use categories are given in Table 1. To encompass the range of topographic conditions and spatial distribution in regard to human settlements, the location of plots was chosen by judgement sampling method which is a non probability sampling method based on the researcher’s own judgements about the representative population (Kothari 1990). The number of plots was proportional to land area under specific land use categories. To increase the normality of the field data, however, the plot area was increased for land use categories with smaller proportions of the total land area (Squiers and Wistendahl 1976). Thus, it increased the proportion of sampled area on these land use categories (Table 1).

Table 1. Details of the sample plots according to land use categories

Land use Category	Area under each land use category(m^2)	Number of sample plots laid *	Length of a side of the squared plot (m)	Area/plot (m^2)	Area of all plots (m^2)	Proportion of Sampled area (%)	Average number of trees per plot	Number of trees in the sample plots (Range)
Reserved Forest	2200000	17	10	100	1700	0.08	15	5-29
Protected Forest	3020000	23	10	100	2300	0.08	15	6-26
Grassland	2570000	18	25	2500	45000	1.75	05	3-8
Cultivated-Irrigated	314400	3	100	10000	30000	9.54	19	8-25
Cultivated-Unirrigated	367000	3	100	10000	30000	8.17	27	17-32
Orchard	70800	3	30	900	2700	3.81	09	6-11
Fallow	28000	3	30	900	2700	9.64	07	5-10
Total	8570200	70			114400	1.33		

*All the plots are square shaped

Note: Total area of the watershed is 8960000 m^2 of which 390000 m^2 is under such uses that has no relevance for vegetative biomass

In every plot, plant diameter at breast height (dbh), i.e., 1.37 m from ground level, was measured with a diameter tape (FSI 2002). Tree height was measured by using a standard inclinometer approach. All trees with a diameter at breast height (DBH) greater than 5 cm, identified to species and their abundance were counted within each sample plot. Stems that split below breast height were counted as separate trees. Diameter and height were used to estimate the above-ground tree biomass with allometric relations as described in next section.

The participatory rural appraisal method was used (Chambers 1994a; Chambers 1994b) to gauge local perceptions about the availability of forest products and of the past and present condition of forest. A household survey was conducted in the watershed to obtain the data relating to human and livestock population. Daily needs of fuel and fodder leaves of all the 102 households in the watershed were recorded on structured schedules. An approximation of average annual requirement for timber and small timber was also obtained from each household during interviews. The quantity was recorded in terms of green weight, which was later converted into air dry weight. This was done to make it comparable to the biomass availability, also estimated as air dry weight. One must keep in mind that due to the extractions from the forests being banned, figures given by the inhabitants are most likely to underestimates the total forest biomass usage.

Biomass estimation methods

Forest biomass was estimated by using allometric equations. Due to the non availability of specific allometric equations for the tree species of study area, we used the following allometric relations available from earlier studies in the adjoining Himalayan region of Nepal (Sharma and Pukkala 1990).

$$\ln v = a + b * \ln(d) + c * \ln(h) \quad (1)$$

where, ln is the natural log, v the stem over bark volume in m^3, d the diameter in cm, h the height in m, and a, b, c are the specie specific parameters available for the dominant species in the watershed.

The over bark volume of each tree obtained from relation (1) is then multiplied by the species specific wood density (WD) to get the stem biomass (SB) in tonnes as follows:

$$SB = v \times WD \quad (2)$$

Species specific wood densities (air dried and with 12% to 15% moisture content) and stem to branch and stem to foliage biomass ratios for different species were obtained through literature search (HMG 1988; Jenkins et al. 2004; Luna 1996; Sharma and Pukkala 1990; WAC 2006). The values of wood density and their sources are presented in Table 2. Although this approach would result in an overestimation of stem biomass because bark was not separated from stem wood in the calculations, it was the best available method for biomass estimation at a landscape scale as demonstrated by earlier studies in the Himalayan region (HMG 1988; Sankhayan et al. 2003; Sharma and Pukkala 1990).

Table 2. Wood densities used in the study and their source

Tree Species	Popular name	Wood density ($kg \cdot m^{-2}$)	Source
Cedrus deodara	Deodar	560	(Sharma and Pukkala 1990)
Celtis australis	Khirk	750	(Luna 1996)
Ficus racemosa	Fehura	480	(WAC 2006)
Grewia optiva	Beyul	800	(Luna 1996)
Pinus roxburghii	chil	650	(Sharma and Pukkala 1990)
Pinus wallichiana	Kail	480	(Sharma and Pukkala 1990)
Juglans regia	Walnut	510	(Jenkins et al. 2004)
Malus domestica	Apple	610	(Jenkins et al. 2004)
Morus alba	Sahtoot	650	(Luna 1996)
Myrica esculanta	Kafal	750	(Sharma and Pukkala 1990)
Prunus armeniaca	Apricot	470	(Jenkins et al. 2004)
Prunus domestica	Plum	470	(Jenkins et al. 2004)
Prunus persica	Peach	470	(Jenkins et al. 2004)
Pyrus communis	Pear	839	(WAC 2006)
Pyrus pashia	Kainth	753	(Luna 1996)
Toona ciliata	Toon	515	(Luna 1996)
Quercus leucotricophora	Oak	1020	(Sharma and Pukkala 1990)

Simulation model

A simulation model developed for tree biomass availability in the watershed is presented in a flow diagram (Fig. 2). It was

written as a set of mathematical equations and solved by using General Algebraic Modelling System (GAMS) (Brooke et al. 1996). The model was run over a time horizon of 30 years to examine the development of tree biomass. The model has the following main equation:

$$B(\mathrm{t}+1,\mathrm{L}) = \frac{\mathrm{e}^{(\rho\text{-}\lambda)} B(\mathrm{t},\mathrm{L})}{[1 + B(\mathrm{t},\mathrm{L})(\mathrm{e}^{(\rho\text{-}\lambda)} - 1) / K(\mathrm{L})]} \tag{3}$$

where, B is the total above-ground biomass, L is the land use category, ρ is the intrinsic growth rate of biomass, λ is the periodic loss due to miscellaneous factors such as decay, fire, illegal felling, etc., K is the carrying capacity of land, and t is time period.

This principal equation of the model is based on the logistic growth model (Renshaw 1991) which explicitly incorporates the idea of carrying capacity. In the protected forest a carrying capacity of 10 tonnes ha^{-1} above the observed mean biomass density is used and the same is based on the discussions with foresters in the watershed who also helped in evolving annual loss to biomass due to miscellaneous factors such as decay, fire, illegal felling, etc. In the land use categories other than forest, carrying capacity of tree biomass is assumed to be constant at the present level. The basis for it lies in the observation that on these privately owned land use categories people find more profitable avenues like crop cultivation and animal grazing than growing more trees on them.

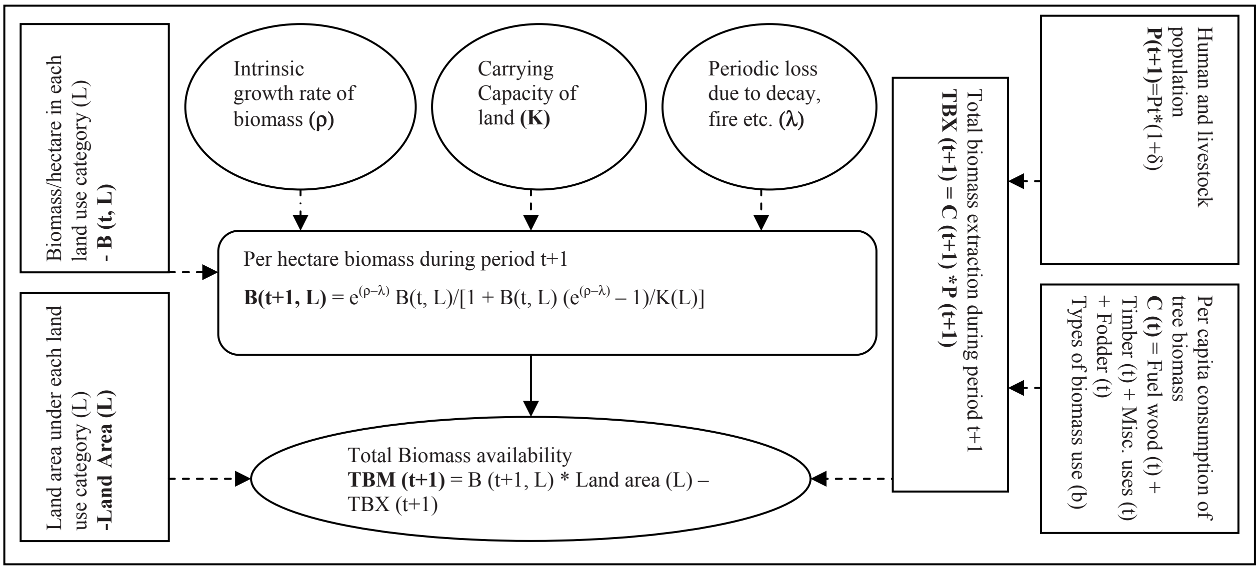

Fig. 2 Flow diagram showing the tree biomass availability and extractions in the watershed

Human and livestock population growth in the model is expressed by:

$$P(\mathrm{t}+1) = P(\mathrm{t}) \times (1+\delta) \tag{4}$$

where, δ is the average annual percent growth rate and P(t) is the total population (human/livestock) in the watershed during year t.

Livestock population was converted into standard livestock units (Anthra 2001). The use of biomass by people in the watershed is expressed by the following equation.

$$TBX(\mathrm{t}) = \sum_{b} C(\mathrm{b},\mathrm{t}) \times P(\mathrm{t}) \tag{5}$$

where, *TBX* is the total biomass extraction, *C* is the per capita consumption of biomass in tonnes, t is the time period, and b represents biomass type, classified as fuel wood, fodder, timber and other uses.

The calibration of model for the base year was done with the help of results obtained from the survey data. For the model time horizon, the basis for the calibration was the past and future perceptions of the people and foresters in the watershed along with our own field observations and the overall trends at state level. The sensitivity analysis was performed to see the relative significance of input variables, such as, growth rates of human and livestock population, periodic losses of biomass, biomass growth rates and carrying capacity, under different model scenarios. Details on precise changes made in different input variables in different model scenarios are given in table 6.

Tree biomass of reserved forest was not included in the model as the use of this forest by the local people is negligible due to severe restrictions, greater distance from village habitations, and relatively lower ratio of fodder trees to total number of trees.

Results

Tree biomass in relation to land use categories and its utilization

The forest in the watershed is dominated by oak (*Quercus leucotricophora*), locally known as 'ban'. Among all other tree spe-

cies found in the forest, it had the highest density of 700 and 830 trees ha^{-1} in reserved and protected forests (Table 3). Cedar (*Cederus deodara*) and chir pine (*Pinus roxburghaii*) were also found in abundance in the watershed forests.

Table 3. Tree species and their biomass attributes on sample plots in different land use categories

Land use category	Species	Popular name	Number of trees	Estimated number of trees per hectare	DBH (cm)			Height (m)		
					Min.	Max.	Mean	Min.	Max.	Mean
Reserved Forest	*Q. leucotricophora*	Oak	119	700	7.5	44.9	16.9	7.0	26.0	14.4
	Cedrus deodara	Deodar	87	512	14.2	98.5	38.9	18.0	41.0	30.0
	Pinus roxburghii	Chil	38	224	14.2	35.4	26.0	14.0	30.0	21.9
	Pinus wallichiana	Kail	5	29	18.9	38.6	26.4	19.0	25.0	22.3
Protected Forest	*Q. leucotricophora*	Oak	191	830	6.4	32.6	15.3	3.5	26.0	14.6
	Pinus roxburghii	Chil	89	387	7.4	49.7	26.6	5.0	36.0	18.9
	Cedrus deodara	Deodar	50	217	11.0	61.5	32.0	9.2	42.0	25.8
	Pinus wallichiana	Kail	20	87	12.2	38.4	22.0	14.0	30.0	22.4
Grassland	*Pinus roxburghii*	Chil	52	12	10.4	32.8	20.5	5.0	25.0	18.4
	Q. leucotricophora	Oak	26	6	8.5	40.5	23.3	7.8	23.0	14.5
	Cedrus deodara	Deodar	2	0	20.2	42.4	31.3	17.8	30.0	23.9
	Celtis australis	Khirk	2	0	10.2	14.6	12.4	14.6	16.8	15.7
	Pyrus communis	Pear	2	0	13.4	14.2	13.8	6.4	6.8	6.6
	Myrica esculanta	Kaphal	2	0	7.6	8.2	15.8	7.4	8.3	15.7
Cultivated-Irrigated	*Prunus persica*	Peach	14	5	6.0	18.2	12.9	5.5	8.0	6.9
	Celtis australis	Khirk	13	4	7.2	87.9	17.5	5.5	24.0	9.4
	Grewia optiva	Beyul	10	3	8.9	15.4	12.0	3.5	7.0	6.0
	Prunus armeniaca	Apricot	5	2	10.2	14.9	12.8	5.5	7.0	6.2
	Cedrus deodara	Deodar	5	2	6.8	22.4	13.4	10.0	24.0	16.8
	Malus domestica	Apple	5	2	8.4	16.7	14.1	5.0	8.0	6.4
	Prunus domestica	Plum	2	1	8.9	9.6	9.3	6.5	7.0	6.8
	Toona ciliata	Toon	1	0	13.4	13.4	13.4	13.5	13.5	13.5
	Ficus racemosa	Fehura	1	0	26.8	26.8	26.8	13.4	13.4	13.4
	Pinus roxburghii	Chil	1	0	15.8	15.8	15.8	20.0	20.0	20.0
Cultivated-Unirrigated	*Grewia optiva*	Beyul	30	10	6.8	21.6	15.3	5.0	26.0	11.8
	Celtis australis	Khirk	21	7	9.8	32.4	17.1	7.0	15.0	10.7
	Prunus armeniaca	Apricot	10	3	10.4	15.4	13.1	5.0	8.0	6.5
	Q. leucotricophora	Oak	7	2	5.6	24.5	15.1	12.0	26.0	17.6
	Prunus domestica	Plum	7	2	10.4	16.4	13.4	5.0	9.0	7.0
	Juglans regia	Walnut	4	1	50.0	80.0	67.5	16.0	30.0	24.8
	Morus alba	Sahtoot	2	1	22.5	24.4	23.5	14.0	15.0	14.5
Orchard	*Malus domestica*	Apple	20	74	6.9	15.4	11.0	4.0	9.5	6.5
	Prunus armeniaca	Apricot	6	22	7.4	15.4	12.1	5.5	9.0	7.4
Fallow	*Celtis australis*	Khirk	8	30	18.6	24.2	21.8	4.0	11.0	7.7
	Q. leucotricophora	Ban	5	19	5.4	20.2	12.9	5.0	14.0	8.4
	Pyrus pashia	Kainth	3	11	9.8	14.2	11.6	5.0	6.0	5.3
	Grewia optiva	Beyul	3	11	16.3	20.2	18.2	5.5	6.5	6.0
	Pinus roxburghii	Chil	1	4	20.4	20.4	20.4	9.8	9.8	9.8
	Morus alba	Sahtoot	1	4	12.6	12.6	12.6	4.5	4.5	4.5

On grasslands, chir pine is the dominant tree species. Highly inflammable pine needles on the floor of this land use category are mainly responsible for forest fires. While interviewing the people in watershed, it was found that fire occurred at an average interval of five to six years in the grasslands and forests. In other land use categories, the number of trees is limited. Since the ownership of these land categories is private, unlike forests, only those trees are grown on the field bunds which have some economic significance, e.g., 'Beyul' (*Grewia optiva*) and 'Khirk' (*Celtis australis*). Peach, apple, apricot and plum fruit trees are grown mainly for self consumption. Being a hail storm prone region, the scope for commercial production of these horticultural crops is limited.

Most of the trees fall in the diameter class of 10 to 20 cm, and belong to the dominant tree species of oak. A very few trees were found in the diameter range of five to 10 cm. Although, trees less than five cm in diameter were not recorded but saplings in the sample plots were found to be rather too few during field observations. Omitting the lowest recorded diameter class, the distribution of trees in dbh classes followed a reverse 'J' shape curve (Fig. 3). By including the lowest diameter classes the diameter distribution curve is reflected by bell shaped curve. This behaviour is more prominent in the protected forests as compared to other land use categories.

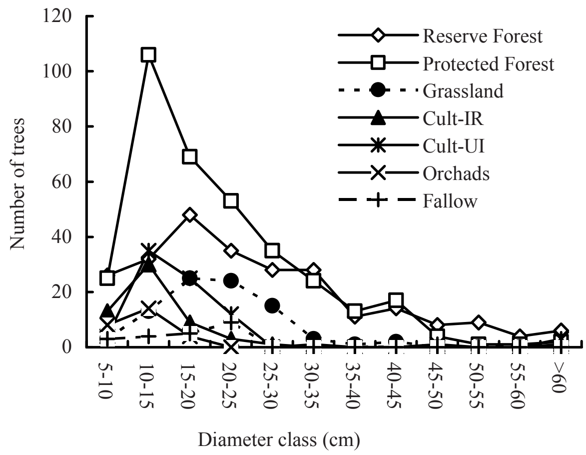

Fig. 3 Diameter class distribution of trees by land use in the sampled plots

Average above-ground tree biomass density in reserved and protected forests was estimated at 1 158 and 728 t·ha^{-1} (Table 4). On other land use categories, biomass density was less than 13.2 t·ha^{-1}. The total tree biomass representing the sum over all species in the forest was found to be distributed among stem, branches and foliage in proportion of 63, 28, and 9. Total above-ground biomass in reserved and protected forests was estimated at 254 700 and 219 900 tonnes, constituting about 99.4% of the total above-ground biomass in the watershed (Table 5). Grasslands accounted for 0.45% of total tree biomass.

The uses of tree biomass as fuel wood, fodder and litter, timber, and for miscellaneous purposes in the watershed were estimated at 522, 120, 50 and 97 tonnes (air dry) per annum, respectively. Utilization of biomass for all purposes is about 0.31% of the total accessible biomass. Per capita fuel wood consumption in the watershed is estimated at 3.56 kg·d^{-1}

Table 4. Estimates of per hectare volume and biomass and related statistics by land use categories

Land use category	Stem volume (m^3·ha^{-1})		Biomass(t·ha^{-1})							
			Stem		Branch		Foliage		Total above-ground	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Reserved Forest	1149.78	757.22	726.90	386.23	325.00	141.66	105.87	46.46	1157.77	543.15
Protected Forest	674.61	491.31	464.83	307.98	201.49	125.40	61.95	31.45	728.27	420.71
Grassland	6.73	4.23	5.13	3.40	2.48	2.95	0.79	0.71	8.40	6.72
Cultivated-Irrigated	2.12	1.72	1.36	1.14	1.17	1.08	0.29	0.24	2.82	2.46
Cultivated-Unirrigated	8.05	7.38	4.98	4.00	4.73	4.59	0.99	0.74	10.70	9.33
Orchard	4.08	2.06	2.33	1.13	1.74	0.84	0.49	0.24	4.56	13.17
Fallow	8.49	3.01	6.84	3.24	4.89	2.61	1.43	0.78	2.21	6.60

Table 5. Estimates of total above-ground tree biomass by land use categories in the watershed

Land use category	Stem (t)	Branch (t)	Foliage (t)	Total above-ground (t)
Reserved forest	159918	71500	23291	254709 (53.36)
Protected forest	140379	60849	18709	219937 (46.07)
Grassland	1319	637	202	2158 (0.45)
Cultivated-Irrigated	43	37	9	89 (0.02)
Cultivated-Unirrigated	183	173	36	393 (0.08)
Orchard	16	12	3	32 (0.01)
Fallow	19	14	4	37 (0.01)

* Figures in parentheses represent percent of total biomass in the watershed

Simulations of biomass changes over next 30 years

The biomass simulation model was run under six alternate scenarios (Table 6), including a base scenario. The selection of the alternate scenarios was guided by the sensitivity analysis, where one of the input variables is changed in each scenario of the model. The model was run for the period 2007–2036 and the result relating to the total biomass availability was compared under different model scenarios.

With the sole exception of BASE scenario, tree biomass was seen rising over the entire simulation period (Fig. 4). In the BASE scenario representing "business as usual", there was relatively a small increase in biomass in the initial years followed by a decline in later years. Results of simulation under the LPGR scenario showed that biomass level can be maintained above sustainable limits through policies aimed at reducing human and livestock population growth rate to half of the existing level and thereby reducing the level of extractions.

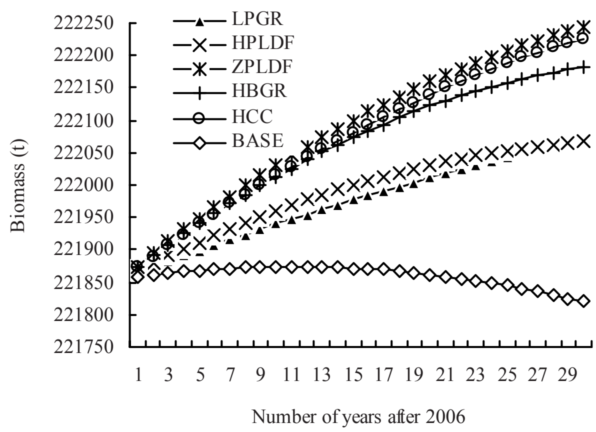

Fig. 4 Simulations for above-ground tree biomass under alternate model scenarios in the watershed over the period 2006-30

Table 6. Brief descriptions of different model scenarios

Number	Abbreviation used for model scenario	Brief explanation of model scenario
1	BASE	Growth rates of 1.60% and 1.04% per annum for human and livestock population. Periodic losses (λ) = 0.51% and intrinsic growth rate of biomass (ρ)= 1.01%.
2	LPGR	The human and livestock population growth rates used in the BASE are lowered to half (0.80% and 0.52%) from existing level.
3	HPLDF	Periodic losses (λ) are reduced to half (0.25) from the level taken in BASE.
4	ZPLDF	Periodic losses (λ) are curtailed to zero.
5	HBGR	Biomass growth rate is halved (0.50%) from the rate taken in BASE.
6	HCC	Carrying capacity of biomass in protected forest is increased by 10 tonnes ha^{-1} than the BASE level.

A reduction in periodic loss of biomass (λ) by 50% than that in the BASE scenario, leads to greater improvement in tree biomass density in HPLDF scenario. Far better results are achieved by curtailing the level to zero as reflected by the fourth scenario ZPLDF. Reduction in population growth rates and λ by 50% has almost similar impact on the output of model. Fourth scenario, ZPLDF gives highest biomass availability in the watershed, thus signifying the need to control the factors influencing these losses. Higher biomass growth rate and carrying capacity, as reflected by the fifth and sixth scenarios give almost similar results. Among all the input variables, a reduction in λ and better growth rate of biomass present a better option for higher sustainability than the reduction in human and livestock population growth rates.

Discussion

The watershed is dominated by Oak (*Quercus leucotricophora*), an evergreen tree having diverse uses for the people, such as, fuel wood, fodder and agricultural mulch (Awasthi et al. 2003; Quazi et al. 2003; Sharma and Verma 2000). Pine forest and grasslands do not have good water retention capacity, leading to forest fires in extremely dry conditions (Rawat 1999). Highly inflammable pine needles on the ground also prevent the growth of grass. Accidental or sometime intentional fire for better fodder yield starts from grasslands with pine trees on lower altitudes and plays havoc to much vegetation in summer months (Bahuguna and Upadhyay 2002). Fodder trees like ‘Beyul’ (*Grewia optiva*) and ‘Khirk’ (*Celtis australis*) are grown on field bunds to meet the green fodder requirements during unexpected long dry spells (Saxena et al. 1997). This type of agri-sivicultural system is prevalent in sub-mountain and mid hills sub-humid zone of Himachal Pradesh (Verma 1988).

The watershed being predominantly located in a forest region with easy access and abundance of useful tree biomass, per capita fuel wood consumption was found to be relatively higher, i.e., 3.56 $kg \cdot d^{-1}$, than that of an average of 1.70 $kg \cdot d^{-1}$ in the forested districts of the state of Himachal Pradesh (Rai and Chakarabarti 1996). It is even higher than the Alpine zone of the state, where, despite severe cold climatic conditions and relatively inadequate power supply, per capita fuel wood consumption is 1.96 $kg \cdot d^{-1}$ (Singh and Sikka 1994). Our estimates compare well with those of forested districts of north eastern states of India (Rai and Chakarabarti 1996). Per capita fuel wood consumption in the Garhwal Himalaya at the same altitude is reported at 2 $kg \cdot d^{-1}$ (Bhatt and Sachan 2004). With improvement in transportation and other infrastructure combined with economic development in the area, several households have started using liquefied petroleum gas (LPG) as a substitute for the fuel wood (Sharma et al. 2007). However, the traditional stoves and fuel wood are still preferred due to economic reasons (Kanagawa and Nakata 2007) for cooking, water heating, space heating, lighting, livestock rearing, etc. Among various activities, cooking requires relatively more energy (Pohekar et al. 2005).

People extract most of the tree biomass during winter months from November to February. During this season less labour is required in agricultural activities and hence the unused labour is often utilised to meet the otherwise increased need of fuel wood and fodder. The fuel wood collected during this period is also stored for future. The extraction is lowest in the rainy season due to availability of green fodder in other land use categories and less fuel wood requirements due to higher temperatures (Bhatt and Sachan 2004).

Small number of trees in the lowest diameter class as reflected by bell shaped curve indicates towards poor regeneration process as against the the reverse ‘J’ shaped size-class distribution curve that is typical of all types of forests (Gove 2003; Shrestha 2005). Insufficient regeneration of trees as reflected in less number of trees in lowest diameter class and too few saplings has also been observed elsewhere in the Himalayan region, and the same is attributed to recurrent disturbances like grazing, fuel wood collection and fire (Farjon and Nigel 1999; Kunwar and Sharma 2004). These observations raise a serious concern about poor regeneration over the last few years. In the Himalayan region such conditions are mainly explained by the anthropogenic pressures (Vetaas 2000). The decline in tree density of low diameter classes in the study watershed can be mainly attributed to open grazing and frequent occurrence of fire and illicit tree felling within this class. Changing climatic conditions (Maikhuri et al. 2003) and occurrence of tree diseases in the region are also contributing to some extent (Karthikeyan et al. 2000; Singh and Lakhanpal 2000). These findings are also supported by some other studies (Singh et al. 1990) and represent the ongoing trend towards forest degradation observed at the state level (FSI 2003).

In this watershed, reserved forest is more distant from the human settlements than the protected forest. The effect of more stringent restrictions in reserved forest is reflected in the difference of biomass density between reserved and protected forests. In addition to geographical advantage, restrictions and distance

from settlements greatly affect the biomass density (Gurung et al. 2002; Sudha et al. 2006). Although, the biomass density is still high in the forest as a whole, people perceive a definite decline in the tree biomass density over the last twenty years.

Magnitude of mean annual increment (MAI) is an important component of the model for knowing the sustainability limits of tree biomass and hence requires careful choice. The parameter of 7.37 $t{\cdot}ha^{-1}{\cdot}a^{-1}$, i.e., 1.01% of the observed mean biomass density of 728.27 tonnes ha^{-1}, was used for MAI in this model. This was based on a recent study in the agro-ecological zones of the western Himalayan region for long rotation forest trees (Ravindranath et al. 2006) . For natural forests in the moist and wet regions of India, MAI is estimated at 7.66 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$ (Singhal et al. 2003), i.e., 0.72% of the observed mean volume of 1 056.94 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$. As the protected forest dominate the total biomass available for utilization in the study watershed, the same value for MAI was used for all land use categories. Some studies, however, show MAI of natural exploitable forest at a relatively low level ranging from 0 to 2 $m^3{\cdot}ha^{-1}{\cdot}a^{-1}$ or sometimes negative due to natural death (Blanchez 1997). Due to these considerations and the specific periodic losses in the watershed as reported by the forest managers and natives, the value of λ is taken at 0.51% (half of the MAI) in this study.

Population growth is regarded as one of the major factors leading to forest degradation in some studies based on simulation models (Sankhayan and Hofstad 2001; Sitaula et al. 2005). Increasing levels of literacy, awareness and economic well-being have shown desirable results in reducing population growth in the state of Himachal Pradesh during recent years (GOHP 2002). The substitution of new breeds of livestock for local breeds and LPG and electricity for fuel will also have favourable effect on lowering biomass demand (NSO 1995; Sankhayan et al. 2007; WECS 2001). Forest fire, illegal felling, unscientific lopping, decay, changing climate, etc., which contribute to ongoing forest degradation also necessitate conservation efforts (Kimothi and Jadhav 1998; Saxena et al. 1997). Besides, being intricately associated with the ecological and hydrological balance, an increase in the biomass density is also beneficial to local inhabitants for whom the forest constitute an important life support system (Singh and Singh 1992). If the factors that affect the biomass loss as depicted by parameter λ are not managed properly, it can reduce forest cover even if overall biomass productivity far exceeds demand (Moench and Bandyopadhyay 1986). The biomass accumulation is also being reduced by changing environmental conditions, irrespective of the current density (Monte-Luna et al. 2004). Such changes due to anthropogenic pressures have adversely affected the carrying capacity of land at both extremes of the moisture gradient (Ehrlich et al. 1989).

K, signifying carrying capacity, was observed to be the most sensitive input variable in the model. An increase of 10 tonnes per hectare in its value over the base period was observed to result in a satisfactory growth of biomass over the model horizon. As should be expected, by bringing the level of periodic loss of biomass (λ) to zero, we get the best results for biomass growth in the model. Such periodic losses, however, cannot be wiped out completely. It can at best be reduced by controlling tree diseases, developmental damages, fire, illegal activities, etc. Increased rate of emigration and substitution of improved breeds of livestock for indigenous breeds have the potential to lower the human and livestock population growth rates thereby resulting in better biomass growth. Though an increase in the biomass growth rate can realise better results, yet such an increase may often be difficult to achieve in the natural forests with human interferences. Appropriate policy interventions as emerging from the behaviour of input variables on model output can ensure almost a continuous rate of increase in biomass, signifying achievement of sustainability. In view of absence of precise estimates of the main affecting parameters, i.e., λ and K, these predictions can at best be taken only as indicative of the system behaviour under various scenarios. This should be helpful in providing useful directions for devising appropriate policies for steering biomass growth in the desired direction.

Conclusion

Estimates of tree biomass and its uses at a micro-watershed level can serve as a useful benchmark for future studies not only in the study areas alone but also in the Himalayan region with similar agro-climatic and socio-economic conditions. Systems behaviour of tree biomass over a period of time can further help adopting appropriate policy options to steer the sustainability goals in this regard. Forest degradation over the last few years as reflected by poor regeneration of trees has serious implications for the sustainability of biomass resource. This calls for suitable policy interventions by the government. Even though the increasing concern shown by the state government has helped protecting the forest area effectively, it has failed to sustain the biomass density over the years in forested areas. The increased restrictions on tree felling in the recent years after the Supreme Court's order have, however, resulted in improvement of biomass stock in the reserved forest. As a result of this decision, a conflicting situation has emerged between managers and local people. It is often not easy to enforce the orders in totality by ignoring the needs and traditional rights of natives. In such conditions, more emphasis is needed to influence supply side factors. Whereas the efforts like tree plantation and removal of decaying trees will augment the regeneration process, a strict check on forest fires and illegal/unscientific extraction of timber and forest products will help in containing periodic losses. Even though the demand side factors have relatively a lesser role in containing the degradation process in this forest dominated region, the efforts to raise higher fuel efficiency by promoting improved cooking stoves, LPG and pressure cookers together with substitution of fewer crossbred livestock to local livestock can be beneficial policy options for lowering fuel wood and fodder demand. Use of briquettes made of pine needles can minimize the risk of fire and can serve as an important substitute for fuel wood. A participatory approach can be a better option for forest protection in an environment where people could realise the ecological and socio economic benefits of the forest rather than adopting a one sided prohibitive approach.

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